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# Maneuvering Rotorcraft Noise Prediction: A New Code For a New Problem<sup>†</sup>

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This paper presents the unique aspects of the development of an entirely new maneuver noise prediction code called PSU-WOPWOP. The main focus of the code is the aeroacoustic aspects of the maneuver noise problem, when the aeromechanical input data are provided (namely aircraft and blade motion, blade airloads). The PSU-WOPWOP noise prediction capability was developed for rotors in steady and transient maneuvering flight. Featuring an object-oriented design, the code allows great flexibility for complex rotor configuration and motion (including multiple rotors and full aircraft motion). The relative locations and number of hinges, flexures, and body motions can be arbitrarily specified to match the any specific rotorcraft. An analysis of algorithm efficiency is performed for maneuver noise prediction along with a description of the tradeoffs made specifically for the maneuvering noise problem. Noise predictions for the main rotor of a rotorcraft in steady descent, transient (arrested) descent, hover and a mild "pop-up" maneuver are demonstrated.

## NOMENCLATURE

$c$  = sound speed in quiescent medium  
 $dl$  = element of the spanwise integration  
 $dS$  = element of the integration surface area  
 $f$  = function defining the integration surface  $f=0$   
 $L_i$  = components of vector defined in Eq.(5)  
 $L_M = L_i M_i$   
 $L_r = L_i \hat{r}_i$   
 $\dot{L}_r = \dot{L}_i \hat{r}_i$   
 $\bar{M}$  = local Mach number vector of source  
 $M_i$  = components of  $\bar{M}$   
 $M = |\bar{M}|$   
 $M_r$  = Mach number of source in radiation direction,  
 $M_i \hat{r}_i$   
 $\dot{M}_i = \partial M_i / \partial \tau$   
 $\hat{n}$  = unit outward normal vector to surface  
 $\hat{n}_i$  = components of  $\hat{n}$

$P_{ij}$  = compressive stress tensor with constant  
 $\rho_0 \delta_{ij}$  subtracted  
 $p$  = pressure  
 $p'$  = acoustic pressure;  $p - p_0$  outside source region  
 $R$  = radius of the blade (see page 8)  
 $r$  = distance between observer and source,  $|\vec{x} - \vec{y}|$   
 $\hat{r}$  = unit vector in radiation direction,  $\hat{r} = |\vec{x} - \vec{y}| / r$   
 $\hat{r}_i$  = components of  $\hat{r}$   
 $t$  = observer time  
 $[T_{i/i-1}(\tau)]$  = general transformation matrix relating frame  
 $i$  to frame  $i-1$  at time  $\tau$   
 $U_i$  = components of vector defined in Eq. (4)  
 $U_n = U_i \hat{n}_i$   
 $U_{\hat{n}} = U_i \partial \hat{n}_i / \partial \tau$   
 $\dot{U}_n = \dot{U}_i \hat{n}_i$   
 $u_i$  = components of local fluid velocity  
 $u_n = u_i \hat{n}_i$   
 $\vec{V}_{P \in i/i-1}$  = velocity of point P of frame  $i$  into frame  $i-1$

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- $v_n$  = local normal velocity of source surface  
 $X$  = first component of the helicopter position in the observer frame  
 $\bar{x}$  = observer position vector  
 $x_i$  = components of  $\bar{x}$   
 $\bar{y}$  = source position vector  
 $y_i$  = components of  $\bar{y}$   
 $Z$  = third component of the helicopter position in the observer frame (altitude)  
 $\bar{\Omega}_{i/i-1}$  = rotation speed of frame  $i$  into frame  $i-1$   
 $\rho$  = density of the fluid  
 $\rho'$  = density perturbation,  $\rho - \rho_0$   
 $\tau$  = source time

#### subscripts

- $L$  = loading noise component  
 $ret$  = quantity evaluated at retarded time  $\tau = t - r/c$   
 $T$  = thickness noise component  
 $0$  = fluid variable in quiescent medium

### INTRODUCTION

Over the past decade, there has been a sustained interest in rotor noise prediction for reasons ranging from noise reduction required by stricter noise standards for civil aircraft to greater stealth in a military environment. A great deal of progress has been made in fundamental theoretical understanding and computational accuracy of both impulsive and non-impulsive noise sources, but evaluation of noise from maneuvering rotorcraft remains a largely untackled and extremely challenging problem. In both civil and military operations, real-world helicopters must maneuver with complex motions, including unsteady, non-periodic conditions, transient effects, pitch, roll and yaw motions: the noise generated is potentially very different from the current steady analysis results. Only recently has the prediction of the noise of a maneuvering rotorcraft been addressed, and no current methods fully model even the simplest maneuvers.

The prediction of maneuvering rotorcraft noise brings with it new computational challenges: 1) rather than an isolated rotor, the complete rotorcraft must be considered to determine its flight path and rotor blade motion; 2) the blade loading and motion can be non-periodic during a maneuver and distinct for each rotor blade; and finally 3) the time scale of even a short maneuver is much greater than a single blade passage, hence the noise prediction must encompass a much longer period of physical time. All current rotor noise prediction codes (e.g., WOPWOP<sup>1</sup>) model only the noise from steady aircraft motion, hence, there is a need for a new code using an algorithm adapted to maneuver noise prediction. Furthermore, the opportunity exists in writing a new code to design it for the unique attributes

of the maneuver problem – including the capability to analyze a very wide array of rotorcraft design features; take advantage of new advanced algorithm innovations for greater computational efficiency; and utilize modern object oriented code design to maximize code flexibility. The first goal of the paper is to outline the algorithm analysis and the development of this new code called PSU-WOPWOP. An algorithm analysis was made (and is presented) to quantitatively evaluate the efficiency of alternative algorithms for the maneuver noise problem. A secondary goal of the paper is to demonstrate the code's capabilities through the prediction of noise for both steady and transient flight conditions. Comparison with the WOPWOP<sup>1,2</sup> noise prediction code is also presented as a first step in validation. Although the code utilizes the theory behind WOPWOP, it is an entirely new code.

### ALGORITHM ANALYSIS

#### Integral formulation

The typical starting point for rotor noise prediction is one of the various forms of the solution to Ffowcs Williams – Hawkins (FW-H) equation<sup>3</sup>. For the PSU-WOPWOP implementation, the FW-H equation for a permeable surface was utilized in the form of the integral representation of the solution known as formulation 1A<sup>4,5</sup>:

$$p'(\bar{x}, t) = p'_T(\bar{x}, t) + p'_L(\bar{x}, t) \quad (1)$$

where  $p'$  is the acoustic pressure,  $\bar{x}$  the observer position,  $t$  is the observer time, and the subscript T and L correspond to thickness and loading components, respectively, and where:

$$4\pi p'_T(\bar{x}, t) = \int_{f=0} \left[ \frac{\rho_0 (\dot{U}_n + U_n)}{r(1-M_r)^2} \right]_{ret} dS + \int_{f=0} \left[ \frac{\rho_0 U_n (r\dot{M}_r + c(M_r + M^2))}{r^2(1-M_r)^3} \right]_{ret} dS \quad (2)$$

and

$$4\pi p'_L(\bar{x}, t) = \frac{1}{c} \int_{f=0} \left[ \frac{\dot{L}_r}{r(1-M_r)^2} \right]_{ret} dS + \int_{f=0} \left[ \frac{L_r - L_M}{r^2(1-M_r)^2} \right]_{ret} dS + \frac{1}{c} \int_{f=0} \left[ \frac{L_r (r\dot{M}_r + c(M_r + M^2))}{r^2(1-M_r)^3} \right]_{ret} dS \quad (3)$$

The dot over a variable implies source-time differentiation of that variable, and a subscript  $r$  or  $n$

indicates a dot product of the vector with the unit vector in the radiation direction,  $\hat{r}$ , or outward surface normal direction,  $\hat{n}$ , respectively. The moving surface considered in the integration is defined by the function  $f(\vec{x}, t) = 0$ ,  $\vec{M}$  is the local surface velocity vector divided by the freestream sound speed. The subscript *ret* denotes that the integrand is evaluated at the retarded time. The vector components  $U_i$  and  $L_i$  are defined as:

$$U_i = \left[ 1 - \frac{\rho}{\rho_0} \right] v_i + \frac{\rho}{\rho_0} u_i \quad (4)$$

$$L_i = P_{ij} \hat{n}_j + \rho u_i (u_n - v_n) \quad (5)$$

### Code Design

Several decisions were made to design and adapt the code to handle maneuver cases efficiently. First, the permeable surface formulation of the FW-H equation (equations 1–5) was chosen so that compressibility effects can be included if the input data is available. In this case the integration surface surrounds the blade, including any nonlinear effects inside the permeable integration surface. Utilization of the formulation in this way enables close coupling with CFD for high-speed impulsive noise computation. Application of the formulation on the blade surface results in the more traditional form of the FW-H equation. Second, an object-oriented approach (implemented in Fortran 95) was chosen to reduce programming errors, increase modularity, and provide flexibility for implementing complex rotor configurations. One new feature of PSU-WOPWOP is the use of task specific data structure objects described further in the paper, such as “rotor”, “blade”, or “patches”. This approach takes advantage of the modern programming practice, and enables the users to efficiently handle any number of rotors, in any arbitrary configuration, for any motion.

To represent the full rotor-blade motion (rotation, flapping, lead-lag, pitch, etc.) and the complete aircraft motion (non-periodic, time-dependent aircraft pitch, roll, yaw, etc.), a series of coordinate transformations from an observer-fixed frame of reference through a set of intermediate reference frames are needed. Namely, all the vector components in the integrand calculation must be expressed in the same frame of reference (usually the observer frame). This problem was considered using the mathematics of a multi-body dynamics problem with many frames of reference, each simple motion leading to a new frame. For the noise computation, the position, velocity and acceleration of each point on the blade, at each source time  $\tau$ , are required. To compute the position of a point belonging to a frame in terms of the previous frame, a simple matrix algebra relation is used:

$$\vec{y}_{(frame\ i-1)} = [\mathbf{T}_{i/i-1}(\tau)] \vec{y}_{(frame\ i)} \quad (6)$$

where  $[\mathbf{T}_{i/i-1}]$  is the general transformation matrix relating the frame  $i$  to the frame  $i-1$ . Therefore, if  $\vec{\eta}$  is a position vector of a point in the blade-fixed frame  $F_N$ , then  $\vec{y}$ , the position vector of the point in the observer-fixed frame  $F_0$  at time  $\tau$ , is simply:

$$\vec{y}(\vec{\eta}, \tau) = [\mathbf{T}_{N/0}(\tau)] \vec{\eta} \quad (7)$$

with  $[\mathbf{T}_{N/0}(\tau)] = [\mathbf{T}_{1/0}(\tau)] \cdots [\mathbf{T}_{i/i-1}(\tau)] \cdots [\mathbf{T}_{N/N-1}(\tau)]$

Instead of differentiating the coordinate transformation matrices to obtain the velocity and the acceleration (as is done in WOPWOP), a method more suitable to maneuver was selected. The formulation is used in the robotics industry to deal with multi-body dynamics problems and is significantly more computationally efficient. This method is based on “torsor” algebra (from the French word “torseur”) instead of matrix algebra.<sup>6</sup>

The velocity of a point P on the blade surface is determined from the Koenig (or Varignon) relation<sup>7</sup>, which relates the velocity of P to the velocity of the origin of the blade  $O_N$ :

$$\vec{V}_{P \in N/0} = \vec{V}_{O_N \in N/0} + \vec{\Omega}_{N/0} \times \overline{O_N P} \quad (8)$$

where  $\vec{V}_{P \in N/0}$  is the velocity of the point P,  $\vec{V}_{O_N \in N/0}$  is the velocity of the point  $O_N$  and  $\vec{\Omega}_{N/0}$  is the rotation speed of frame N (blade frame) in the frame 0 (observer frame). The velocity of the center of frame N and the corresponding rotation speed are computed using the composition of motion relations:

$$\vec{\Omega}_{N/0} = \vec{\Omega}_{1/0} + \cdots + \vec{\Omega}_{i/i-1} + \cdots + \vec{\Omega}_{N/N-1} \quad (9\ a)$$

$$\vec{V}_{O_N \in N/0} = \vec{V}_{O_N \in 1/0} + \cdots + \vec{V}_{O_N \in i/i-1} + \cdots + \vec{V}_{O_N \in N/N-1} \quad (9\ b)$$

where the right hand sides are the given motion data. Although the acceleration field cannot be represented by a “torsor”, we can use similar relations to compute the acceleration.

This approach to the kinematics enabled us to significantly reduce the number of operations involved in the motion description: the operation count for velocity and acceleration computation is proportional to number of transformations  $N$ , instead of  $N^2$  and  $N^3$  respectively for matrix algebra. For example, matrix algebra requires  $9N^3 + 15N$  operations to compute the acceleration of a point. In contrast, the new approach uses only  $150N + 33$  operations to calculate the acceleration of a point on the integration surface. This method proves to be more efficient for maneuver cases,

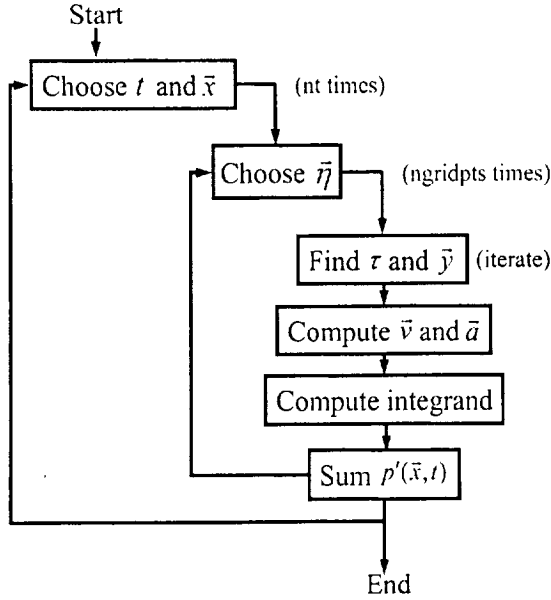


Figure 1. Schematic of retarded-time algorithm.

where  $N$  becomes large. For example, if  $N = 13$  (as in the transient maneuver cases which follow) the operations count is reduced by a factor 10. Similar savings of computational effort are realized in the velocity calculations as well.

#### Algorithm Efficiency Analysis

Once the acoustic formulation and motion description were determined, an analysis of the integration algorithm was performed. Although formulation 1A is a retarded-time formulation, there are several approaches to finding the acoustic pressure time history with this formulation. The most common method of solution, which we shall call the “retarded-time” algorithm, is used in WOPWOP<sup>1</sup>. The solution procedure starts with the choice of the observer time  $t$  at which the solution is desired. For each point on the integration surface, the blade is iteratively repositioned to determine where that point was when the sound was emitted, hence satisfying the retarded-time equation,  $\tau = t - |\bar{x} - \bar{y}(\tau)|/c$ . The retarded-time  $\tau$  is the time at which the sound reaching the observer at time  $t$  was emitted. Notice that in this equation the source position  $\bar{y}(\tau)$  is function of the retarded time.

An alternative to the retarded-time algorithm is to use the same formulation, but to fix the source time  $\tau$  and determine when the sound from each point on the blade surface will reach the observer. Since the arrival time  $t$  will be different for each point, the time history of each point on the surface must be interpolated so that the contributions can be summed at the same observer

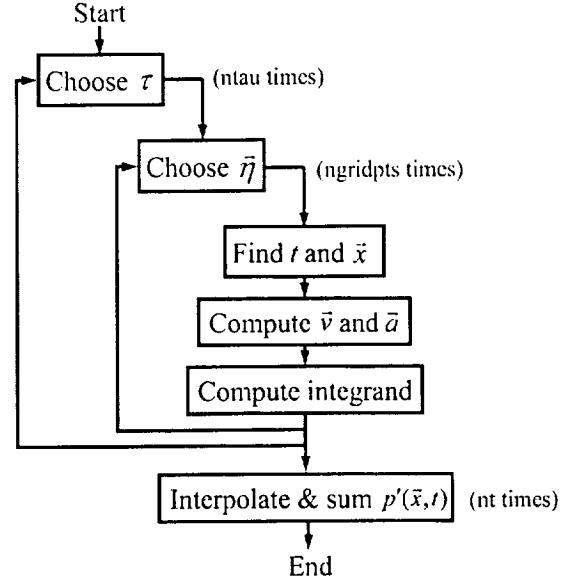


Figure 2. Schematic of source-time-dominant algorithm.

time  $t$ . We call this algorithm a “source-time-dominant” algorithm, however others have called variations of this approach a “binning technique.”<sup>8</sup> In both the retarded-time and source-time-dominant approaches, once the appropriate time is found for a point on the blade surface, the integrand at that point may be determined, using equations (2) and (3).

In both algorithms, the coordinate transformation matrices are needed to find the source position at the emission time. All transformation matrices  $[T]$  are functions of the source time  $\tau$  and independent of the observer time  $t$ . The computation costs, however, are significantly different for the two algorithms. In retarded-time approach,  $[T]$  must be computed for each point on the grid, for each observer time  $t$ —including an iteration to find the particular source  $\tau$  that satisfies the retarded-time equation  $(\tau = t - |\bar{x} - \bar{y}(\tau)|/c)$ .

Figure 1 shows a schematic of the retarded-time algorithm. On the other hand, the “source-time-dominant” algorithm only requires one evaluation of the coordinate transformation, for each source time  $\tau$ , since the transformation matrices  $[T]$  are the same for each point on the grid ( $\tau$  is fixed). A schematic of the source-time-dominant algorithm is shown in figure 2.

The coordinate transformations are involved not only in the computation of the blade position, but also in the calculation of the source point velocity and acceleration as well. The number of floating point operations is proportional to the number of coordinate

transformations used. The source-time-dominant approach appears to be more attractive because coordinate transformations only need to be computed once for each source time. This is particularly important since a significant number of frames are expected. However, this approach contains two potential drawbacks. First, in the source-time-dominant algorithm, the arrival time of the acoustic signal will be different for each point on the blade; hence, the time history for each point must be interpolated so that the contribution from each source point can be summed at the same observer time. This additional step is shown at the bottom of Figure 2. Another potential issue is that more points may be required in the source time history than in the acoustic-pressure time history ( $n\tau \gg nt$ ). This would occur when high temporal resolution is required, such as in the case of blade-vortex interaction (BVI). Consequently, more integrand computations might be performed in the source-time-dominant approach, even though the number of coordinate transformation computations is significantly reduced.

To help clarify which algorithm is more efficient for computing the noise of maneuvering rotors, an analysis of operation counts for each of the two algorithms was performed and the important parameters identified (i.e., number of points on the integration surface— $n_{gridpts}$ , number of input data points in the source-time history— $n\tau$ , number of output points in the observer-time history— $nt$ , number of coordinate transformations, etc.). Experience with WOPWOP guided the analysis, and as expected, one of the most significant parameters was the number of coordinate transformations. The other parameters of particular importance for maneuver noise prediction were the number of points in the observer time history and the ratio  $nt/n\tau$ . In figures 3 and 4, the height of the surface shows the expected operation count for both the retarded-time and source-time-dominant algorithms. The number of operation is plotted as a function of the number of coordinate transformations (right lower axis) and the number of points in the observer-time history  $nt$  (left lower axis). In figure 3, the ratio  $nt/n\tau$  is equal to 3, which corresponds to a case where the observer-time resolution is finer than the source-time resolution. This is typical of the case for transient maneuver, with long time scale (large  $nt$ ) and rather low-resolution time-dependent loading (data available only every 10 degrees or so). From the figure, it is clear that the source-time-dominant algorithm requires significantly less floating-point operations, especially for large number of coordinate transformations. Figure 4 shows the same comparison for a ratio  $nt/n\tau$  equal to 0.2. The situation corresponds to a case where high-resolution loading data is available (e.g., data every half degree). This level of resolution is necessary for accurate computation

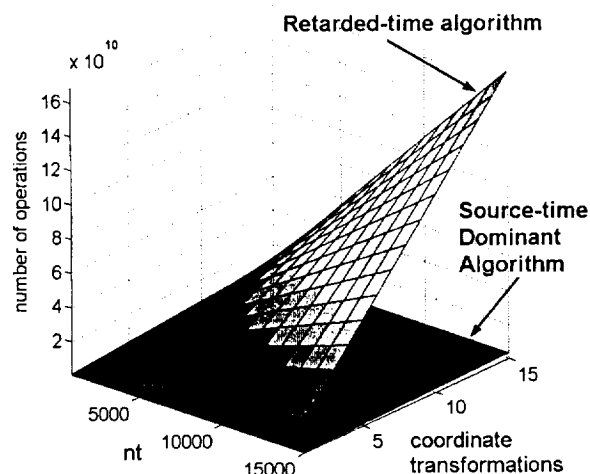


Figure 3: Comparison of operation count for retarded-time and source-time-dominant algorithm for the ratio  $nt/n\tau = 3$ .

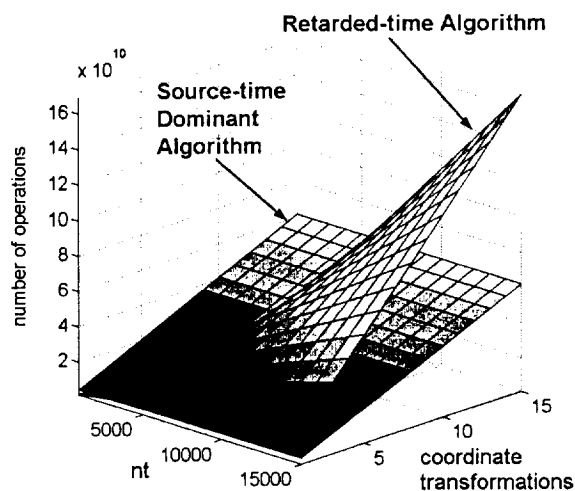


Figure 4: Comparison of operation count for retarded-time and source-time-dominant algorithm for the ratio  $nt/n\tau = 0.2$ .

of blade-vortex-interaction noise and other impulsive noise sources. Once again, the source-time dominant approach is more attractive for maneuver, even though the retarded-time algorithm requires fewer operations for a small observer time history. The number of coordinate transformations and the time scale are expected to be large for the prediction of maneuvering rotor noise (maybe as many as 15 coordinate transformations, up to 30-second time history).

Therefore, based on this analysis, it was decided to use the source-time-dominant algorithm.

### THE MANEUVER CODE

#### Object Oriented Design

The object-oriented design is one of the new features in PSU-WOPWOP. Several task specific data structures together with associated functions to operate on the data effectively define "objects" in the code implementation. Objects are organized in a hierarchy for convenience. The lowest level object is known as a "patch", which contains the two-dimensional surface definition of the a piece of the blade surface, along with related quantities such as surface loading and normal vectors. Arrays of "patches" form objects known as "blades". Each "blade" contains additional information that is common among all the patches. Collections of "blades" are known as a "rotor" which also contains data relevant to all the blades. A configuration can contain several "rotor" objects. During implementation this hierarchy of objects helped reduce the number of coding errors and assisted testing operations. To implement the general motion formulation described previously, another type of data structure was introduced to efficiently characterize the coordinate transformation from one coordinate basis to another. An array of these coordinate transformations is used to construct each transformation needed for arbitrarily complex rigid body motion. This approach gives users great flexibility to implement with multiple rotors, multiple blades with any spacing or shape and any arbitrary motion.

#### Chordwise Compact Formulation

While the acoustic formulation described in equations (1)–(5) assumes that the fluid pressure and velocity are provided all over the integration surface, often only the blade loading as a function of rotor radius is available from a comprehensive analysis. Brentner et al.<sup>9</sup> have shown that a chordwise compact model for loading noise is reasonably accurate away from the rotor tip-path plane. Brentner and Jones<sup>2</sup> developed a chordwise compact loading noise formulation that can be written:

$$4\pi p'_L(\vec{x}, t) = \frac{1}{c} \int_{r=0}^{\bar{L}} \left[ \frac{\dot{L}_r}{r(1-M_r)^2} \right] dl + \int_{r=0}^{\bar{L}} \left[ \frac{L_r - L_M}{r^2(1-M_r)^2} \right] dl + \frac{1}{c} \int_{r=0}^{\bar{L}} \left[ L_r \frac{(r\dot{M}_r + c(M_r + M^2))}{r^2(1-M_r)^3} \right] dl \quad (10)$$

In this formulation,  $\bar{L}$  is the section loading vector, and  $l$  is the spanwise integration variable. Although the

thickness noise still requires chordwise integration, this approximation makes the loading noise computation compatible with comprehensive analysis input data and significantly reduces the computational cost of the loading noise prediction. In the code, the compact loading noise is implemented as a "compact loading" patch object. Since thickness and compact loading noise are computed on separated patches, the source time scales can be different for each patch. This feature could be very efficient for BVI computation—source-time resolution must extremely precise for loading to accurately capture BVI, while the thickness noise time discretization can be relatively coarse.

### CODE AND METHODOLOGY VALIDATION

#### Loading Computation

The acoustic prediction requires the determination of the blade motion and loading. A comprehensive analysis code is ultimately required to provide the rotor trim conditions even if relatively sophisticated computational aerodynamic and structural dynamic codes are also used. If the comprehensive analysis code is used alone, then the usual questions of adequacy of the dynamic stall, unsteady aerodynamics, and wake models are compounded by the complication of maneuvering flight. For this work, the CAMRAD 2 comprehensive analysis code<sup>10</sup> has been utilized.

In typical trim computations, a series of complicated non-linear algorithms is solved using highly damped versions of Newton's method (other methods are also available). The algorithms are "nested" within each other in a way to minimize run-time. Note also that various functions of the system interact at several different "levels" of the iteration. The control vector is systematically updated to achieve solution convergence. One of the more useful features of the CAMRAD 2 code is that it allows the user complete access to the numerical scheme. It is particularly easy, for example, to exercise complete control over damping convergence of the models.

The arrested descent maneuver was computed using the transient flight option available in the CAMRAD 2 model. Transient maneuvers are complex—neither blade motion nor loading are periodic. Thus, the fundamental assumption of periodicity is invalid. The forces and moments are integrated to obtain the response at each time step due to specified control input. A solution set from a previous trim is used to initiate the computation. For the present application, there are three things to note about this approach. First, since the solution is no longer periodic, it is necessary to treat each blade as a separate component. Second, the solution requires that the control settings be specified *a priori*. Third, the procedure does not routinely include a sub-iteration mechanism to stabilize the numerical integration—a shortcoming that leads to the

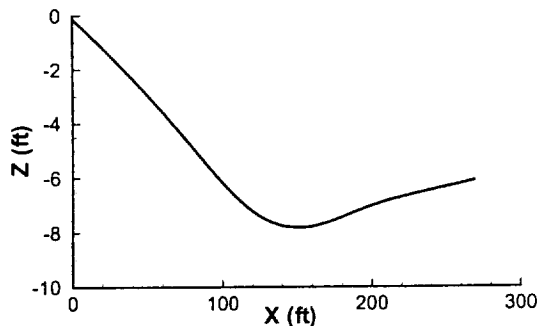


Figure 5: Aircraft height during arrested descent maneuver.

accumulation of truncation, round-off and convergence errors that may eventually destroy a computation which is allowed to run too long. The transient used in the current example problem was chosen to be short in duration ( $\sim 2$  sec) and hence avoided an accumulation of time-integration error.

Typically, the trim and maneuver algorithms rely heavily upon semi-empirical models of the various physical phenomena that must be addressed in the solution. A full discussion of all these models is far beyond the scope of this paper but is presented by Johnson<sup>10</sup>. The key modeling assumptions employed in this work will now be reviewed. A notional four-bladed, articulated-rotor aircraft of approximately 14,000 pounds gross weight was used in this study. Since these computations are only intended to demonstrate the utility of PSU-WOPWOP code, details of the rotor and aircraft models were not chosen to correspond with any existing aircraft. The aircraft model includes main and tail rotors together with fuselage aerodynamics. Dynamic and structural responses for both rotors are computed. A rigid fuselage is assumed. The blade was modeled with 25 unequal radial segments.

The transient maneuver calculation in CAMRAD 2 was performed with an integration time step of 0.002885 seconds ( $\sim 5$ -degree azimuth step) and the blade response time history was saved at 0.005770 second intervals ( $\sim 10$ -degree azimuth step). Blade loading computed at 5-degree azimuthal increments is insufficient to adequately characterize BVI, yet was deemed acceptable since the focus in this paper on the acoustic code development and not BVI noise prediction. The transient maneuver computation was fully time-dependent (not quasisteady), but for simplicity both the main and tail rotor aerodynamics were computed using dynamic inflow rather than a more computationally intensive free wake. Lift and drag forces were resolved in a blade fixed system and were extracted for each blade as a function of time. Blade flap, lag, and pitch hinge displacements were also extracted as functions of time for each individual blade.

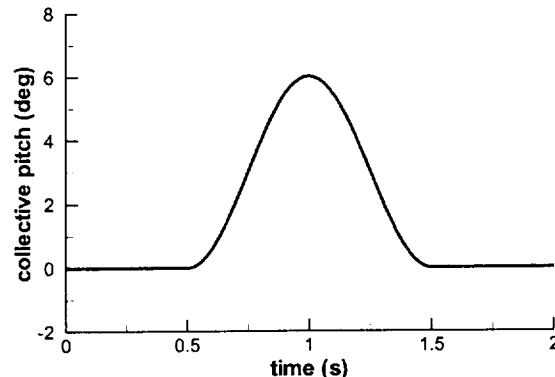


Figure 6: Time history of collective pitch for the three-degree arrested descent maneuver.

The time history of the aircraft pitch, roll, and yaw orientations and the location of the aircraft center of gravity are computed and saved for the acoustic computation.

#### Transient Test

To validate the new PSU-WOPWOP code, a comparison with WOPWOP predictions<sup>†</sup> is presented for a three-degree arrested descent. This maneuver is representative of a short-time transient maneuver, with both non-periodic blade motion and loading. The total time of the maneuver was 2 seconds; with a moderate helicopter forward speed of 40m/s. Figure 5 shows the change of aircraft altitude. The descent of the helicopter was arrested using a collective pulse control input described in figure 6.

The rotor blade has a linearly twisted blade of radius 7.32m with 20-degree tip sweep, described by two patches (upper and lower surface). The computation was performed for the main rotor, with four equally spaced blades. The observer was fixed and located 100 feet below the helicopter center of gravity at source time  $\tau=0$ . Therefore, the signal was received at the observer position shortly after the helicopter has flown over. Under those conditions, the loading noise happens to be dominant (thickness noise is completely negligible). The comparison between the two loading noise predictions is shown on figure 7. Although both codes are based on the same formulation, the algorithms used are completely different, and an excellent agreement is obtained between the two codes. The computation time, however, is significantly less for the PSU-WOPWOP computation than for WOPWOP computation.

<sup>†</sup> The WOPWOP results are from Brentner and Jones<sup>2</sup>. Note the version of WOPWOP used by Brentner and Jones was modified to perform maneuver computations specifically to determine the importance of transient maneuver on noise generation. This code has not been distributed.



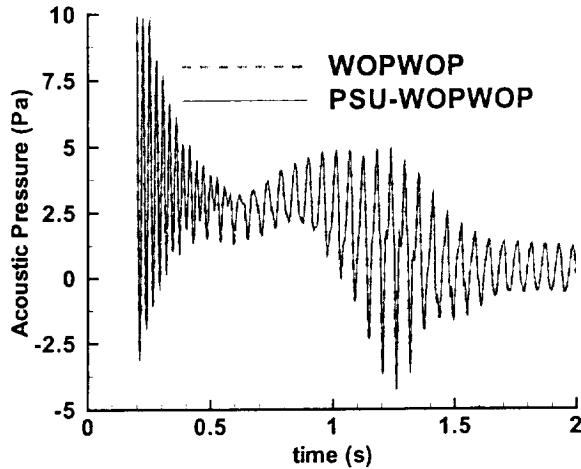


Figure 7: Acoustic pressure comparison for a three-degree arrested descent.

The transient loading computation of Brentner and Jones<sup>2</sup> was used as input for both of the noise predictions in figure 7. This loading computation was inadvertently based upon the uniform inflow model rather than the intended dynamic stall model. (A free-wake model was not used in order to minimize the complexity of the analysis for maneuver.) For this paper, the three-degree arrested descent was rerun with the dynamic inflow model. The PSU-WOPWOP noise computation is compared with the previous result in figure 8. The most significant difference between these computations is the beginning of the time history—before the maneuver has begun. An investigation into the cause of the difference reveals one of the most challenging problems in computing the loading for a helicopter in maneuver: achieving stability and convergence of the time dependent integration. The normal force time history at a radial station  $r/R = 0.9325$  in figure 9 illustrates apparent numerical oscillations during the first one-half second of the computation. Notice in figure 9 that only the uniform inflow result contains high-frequency oscillations while that from the dynamic inflow model is significantly smoother. This does not imply that the uniform inflow model is fundamentally flawed, but rather illustrates that the numerical procedure used to transition from a steady case to a transient case is tricky—and in this example leads to oscillations. Although these oscillations appear to be entirely numerical in nature, they are of critical importance to the acoustic computation. The time derivative of the normal force at this radial station is shown in figure 10. Here the effect of the oscillations is very clear during the first one-half second (the “steady” part of the maneuver).

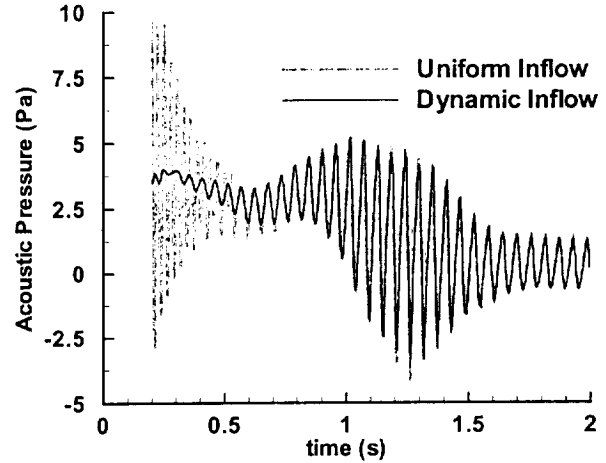


Figure 8: Comparison of noise computed by PSU-WOPWOP with loading from uniform inflow and dynamic inflow models.

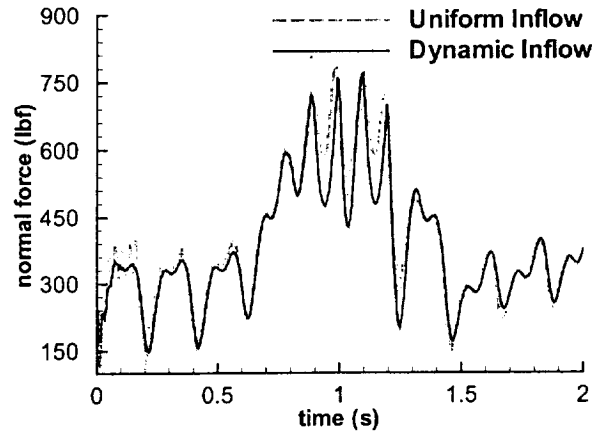


Figure 9: Time history of normal force at  $r/R = 0.9325$  for both uniform and dynamic inflow models.

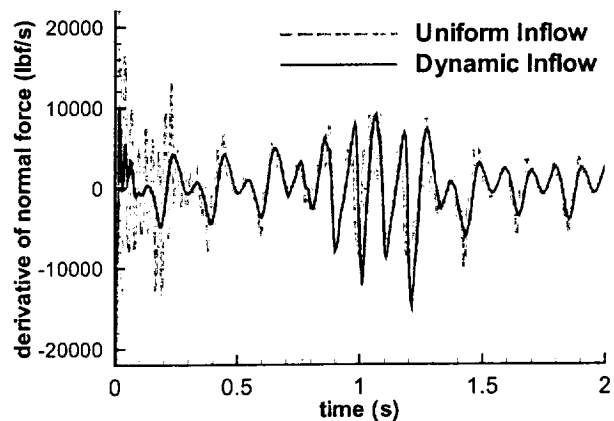


Figure 10: Time history of normal force derivative at  $r/R = 0.9325$  for both uniform<sup>5</sup> and dynamic inflow models.

Arrested Descent maneuver	Computation time (thickness and loading noise)	Computation time (loading noise only)
WOPWOP	315 s	
PSU-WOPWOP	5.73 s	1.21 s

Table 1. Comparison of run-times on a 1.7 GHz Pentium Xeon processor.

As a validation of the algorithm analysis used for the code PSU-WOPWOP code design, the execution time of WOPWOP<sup>†</sup> is compared to PSU-WOPWOP in Table 1 for the arrested descent maneuver. All the computations were performed on a 1.7 GHz Pentium Xeon processor. As expected, there is a significant improvement in calculation time with the PSU-WOPWOP algorithm—a 55 times speed up as compared to WOPWOP—mainly due to the new code design and the run-time efficiency analysis performed. As mentioned earlier, WOPWOP uses derivatives of the transformation matrices for velocity and acceleration computation. Recall that with  $N$  coordinate transformations, the number of operation to compute velocity and acceleration are proportional to  $N^2$  and  $N^3$  instead of  $N$ , for each point on the integration surface at each point in the observer time history. The source-time-dominant approach in PSU-WOPWOP really pays off here with 13 transformations used to represent the full aircraft motion. Furthermore, in this computation thickness noise is negligible, and is easily disabled in the PSU-WOPWOP code, resulting in an even faster execution time of approximately 1.2 seconds for a maneuver which requires 1.8 seconds to complete.

#### Acoustic Impact of Transient Maneuvers

Now, to demonstrate the impact of transient maneuver on the rotor noise, the previous result was compared with the noise generated during a three-degree steady descent, for the same helicopter/observer configuration (figure 11). As expected, the results are identical during the first 0.6 seconds of the maneuver, which correspond to the steady part of the arrested descent. Then, the amplitude of the acoustic pressure increases significantly (by nearly a factor of four) during the transient phase corresponding to the adjustment of collective pitch to arrest the descent.

A similar comparison of predicted noise was made between a hovering rotor and a mild “pop-up” maneuver. For both cases, the blade rotation speed is 293 RPM, and the observer is stationary at 100 feet below the helicopter center of gravity and 100 feet in

front of it, at source time  $\tau=0$ . Figure 12 shows the change in aircraft altitude as a function of time while figure 13 shows the aircraft attitude during the “pop-up” maneuver. The total duration of the maneuver was 2 seconds. The same rotor configuration (described earlier) was used for these computations. Once again, the thickness noise is negligible. The comparison of the loading noise for each of these maneuvers is shown in figure 14. As expected, the acoustic pressure is periodic for the hover case, and matches exactly the first one-half second of the pop-up maneuver, where the altitude  $Z$  of the helicopter remains approximately constant, and equal to the hover altitude. The acoustic impact of the maneuver is then clearly identifiable, as the amplitude of the acoustic pressure in the “pop up” maneuver is nearly three times that of the hovering rotor.

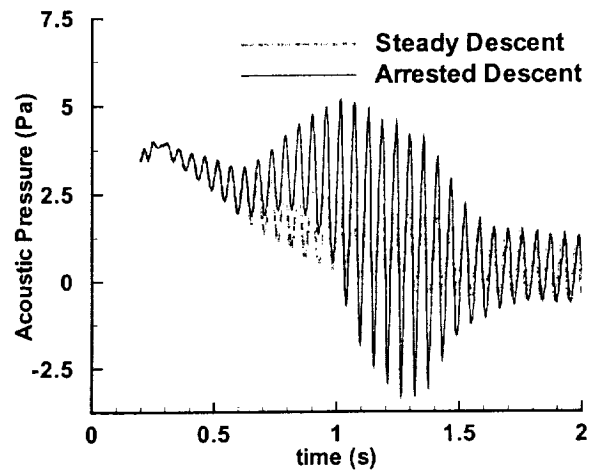


Figure 11: Comparison of acoustic pressure time history computed with PSU-WOPWOP for a three-degree steady descent and an arrested descent maneuver.

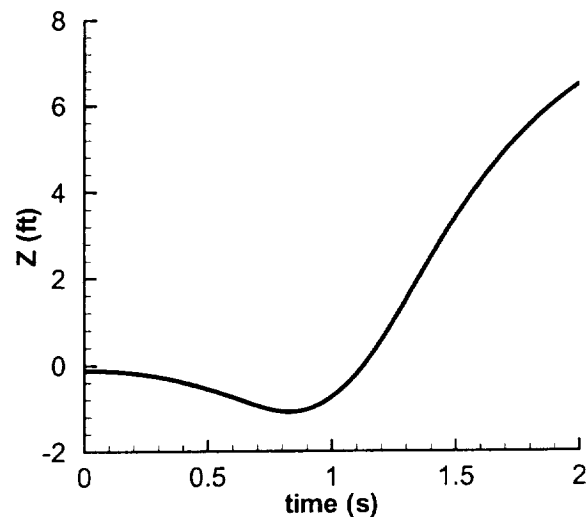


Figure 12: Change in aircraft altitude during the pop-up maneuver.

<sup>†</sup> The maneuver version of WOPWOP developed by Brentner and Jones<sup>2</sup>.

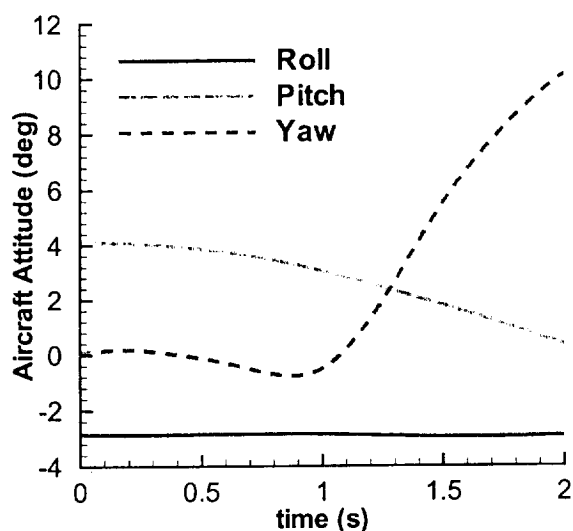


Figure 13: Change in aircraft attitude (roll, pitch and yaw) during the pop-up maneuver.

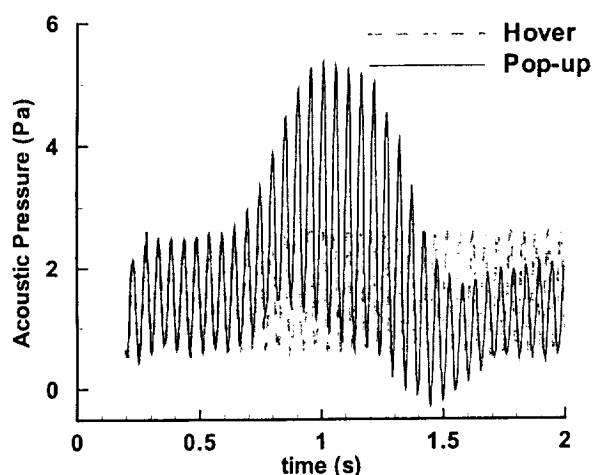


Figure 14: Comparison of acoustic pressure time history computed with PSU-WOPWOP for a hover and mild "pop up" maneuver.

#### CONCLUDING REMARKS

Although the prediction of the noise generated by a maneuvering rotor remains challenging, this paper begins the process of identifying the unique features of maneuver noise that require appropriate acoustic modeling. The main focus of the paper was the design and development of a new code for maneuvering rotorcraft noise prediction called PSU-WOPWOP. Both steady and transient flight conditions can be modeled, with arbitrary aircraft and blade motions, for periodic or time-dependent data. The usual assumption that the blade is a rigid body remains, but otherwise, the relative locations and number of hinges, the blade shape and spacing can be specified to match any specific

rotorcraft. The multiple rotor capability enables computation for any rotor configuration (i.e. main/tail rotor interaction, tilt rotors, etc.). The compact-chordwise loading formulation has been implemented to make the code more compatible with comprehensive analysis codes. The impact of maneuver on rotor noise radiation was demonstrated for a three-degree arrested descent and a mild "pop up" maneuver—in each case the amplitude of the noise during the transient maneuver is significantly higher than for the related steady condition. In conclusion, PSU-WOPWOP has great potential to become a standard noise prediction code for maneuvering rotor.

#### ACKNOWLEDGMENTS

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